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Die beiliegenden Akten stimmen überein mit den ursprünglichen Unterlagen der auf den nächsten Seiten bezeichneten, beim unterzeichneten Amt als Anmeldeamt im Sinne von Art. 10 des Vertrages über die internationale Zusammenarbeit auf dem Gebiet des Patentwesens (PCT) eingegangenen Patentanmeldung.

Attestation

Les documents ci-joints sont conformes aux pièces originales relative à la demande de brevet spécifiée aux pages suivantes, déposées auprès de l'Office soussigné, en tant qu'Office récepteur au sens de l'article 10 du Traité de coopération en matière de brevets (PCT).

Confirmation

It is hereby confirmed that the attached documents are corresponding with the original pages of the international application, as identified on the following pages, filed under Article 10 of the Patent Cooperation Treaty (PCT) at the receiving office named below.

PRIORITY DOCUMENT
SUBMITTED OR TRANSMITTED IN COMPLIANCE WITH RULE 17.1(a) OR (b)

Berne, le 02 septembre 2003

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Patentverfahren
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Patent Administration

Rolf Hofstetter

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PCT REQUEST

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0	For receiving Office use only	
0-1	International Application No.	PCT/CH 02/00481
0-2	International Filing Date	02. Sep. 2002 (02.09.02)
0-3	Name of receiving Office and "PCT International Application"	RO/CH - Internationale Anmeldung PCT

0-4	Form - PCT/RO/101 PCT Request	
0-4-1	Prepared using	PCT-EASY Version 2.92 (updated 01.06.2002)
0-5	Petition The undersigned requests that the present international application be processed according to the Patent Cooperation Treaty	
0-6	Receiving Office (specified by the applicant)	Swiss Federal Intellectual Property Institute (RO/CH)
0-7	Applicant's or agent's file reference	13-20.B.WO-P
I	Title of invention	THREE AXIS ACTIVE MAGNETIC LEVITATION FOR INERTIAL SENSING SYSTEMS
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V	Designation of States	
V-1	Regional Patent (other kinds of protection or treatment, if any, are specified between parentheses after the designation(s) concerned)	AP: GH GM KE LS MW MZ SD SL SZ TZ UG ZM ZW and any other State which is a Contracting State of the Harare Protocol and of the PCT EA: AM AZ BY KG KZ MD RU TJ TM and any other State which is a Contracting State of the Eurasian Patent Convention and of the PCT EP: AT BE BG CH&LI CY CZ DE DK EE ES FI FR GB GR IE IT LU MC NL PT SE SK TR and any other State which is a Contracting State of the European Patent Convention and of the PCT OA: BF BJ CF CG CI CM GA GN GQ GW ML MR NE SN TD TG and any other State which is a member State of OAPI and a Contracting State of the PCT
V-2	National Patent (other kinds of protection or treatment, if any, are specified between parentheses after the designation(s) concerned)	AE AG AL AM AT AU AZ BA BB BG BR BY BZ CA CH&LI CN CO CR CU CZ DE DK DM DZ EC EE ES FI GB GD GE GH GM HR HU ID IL IN IS JP KE KG KP KR KZ LC LK LR LS LT LU LV MA MD MG MK MN MW MX MZ NO NZ OM PH PL PT RO RU SD SE SG SI SK SL TJ TM TN TR TT TZ UA UG US UZ VC VN YU ZA ZM ZW
V-5	Precautionary Designation Statement In addition to the designations made under items V-1, V-2 and V-3, the applicant also makes under Rule 4.9(b) all designations which would be permitted under the PCT except any designation(s) of the State(s) indicated under item V-6 below. The applicant declares that those additional designations are subject to confirmation and that any designation which is not confirmed before the expiration of 15 months from the priority date is to be regarded as withdrawn by the applicant at the expiration of that time limit.	
V-6	Exclusion(s) from precautionary designations	NONE
VI	Priority claim	NONE
VII-1	International Searching Authority Chosen	European Patent Office (EPO) (ISA/EP)

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VIII	Declarations	Number of declarations	
VIII-1	Declaration as to the identity of the inventor	-	
VIII-2	Declaration as to the applicant's entitlement, as at the international filing date, to apply for and be granted a patent	-	
VIII-3	Declaration as to the applicant's entitlement, as at the international filing date, to claim the priority of the earlier application	-	
VIII-4	Declaration of inventorship (only for the purposes of the designation of the United States of America)	-	
VIII-5	Declaration as to non-prejudicial disclosures or exceptions to lack of novelty	-	
IX	Check list	number of sheets	electronic file(s) attached
IX-1	Request (including declaration sheets)	5	-
IX-2	Description	12	-
IX-3	Claims	1	-
IX-4	Abstract	1	EZABST00.TXT
IX-5	Drawings	6	-
IX-7	TOTAL	25	
	Accompanying items	paper document(s) attached	electronic file(s) attached
IX-8	Fee calculation sheet	✓	-
IX-17	PCT-EASY diskette	-	Diskette
IX-19	Figure of the drawings which should accompany the abstract	1	
IX-20	Language of filing of the international application	English	
X-1	Signature of applicant, agent or common representative		
X-1-1	Name (LAST, First)	ROLAND, André	

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10-2	Drawings:	
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10-3	Corrected date of actual receipt due to later but timely received papers or drawings completing the purported international application	
10-4	Date of timely receipt of the required corrections under PCT Article 11(2)	
10-5	International Searching Authority	ISA/EP
10-6	Transmittal of search copy delayed until search fee is paid	

FOR INTERNATIONAL BUREAU USE ONLY

11-1	Date of receipt of the record copy by the International Bureau	

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J.W. Beams, Magnetic Bearings, Automotive Engineering Congress, Detroit, Mich., January, 1964.

W.J. Bencze, Y. Xiao, D.N. Hipkins, B.W. Parkinson, G.F. Franklin, An Electrostatic Suspension and Orientation Control System for the Gravity Probe B Relativity Mission's Science Gyroscope, 3rd MOVIC, September 1996, Chiba, Japan.

Abstract/ Introduction :

Field: precision instrumentation, magnetic bearing, non-contact seismic sensors, non-contact accelerometer, non-contact tiltmeter, non-contact gyroscope, non-contact gravimeter.

The present invention relates to high sensitivity multi-axis measuring devices based on the magnetic levitation of a ferromagnetic body.
The possible applications range from accelerometers to gravimeters, high precision seismometers, tilmeters and gyroscopes.

Prior Art :

For seismologists, it is relevant to study seismic waves within the following ranges:
- Frequencies: From 1mHz to 100Hz
- Accelerations : From 1 nano g to 5 g

Given this wide spread both of the relevant frequencies and the relevant accelerations which need to be recorded and analysed, several classes of measuring instruments have been developed :

- Short Period seismic sensors
- Long Period seismic sensor
- Broad band seismic sensors
- Very broad band seismic sensor

All the corresponding products presently commercialised are designed around a damped mechanical mass-spring system made up of a mass detector linked both to a damping mechanism and, with a spring, to the frame of the instrument.

In the case of a seismic input, the frame of the seismometer follows the ground movement while the mass used as a detector, which we shall designate as the seismic mass, tends to remain in its initial position, thus moving relatively to the frame.

In the process the length of the spring changes and the displacement in relation

to the frame can be measured as a function of time.

The response to a seismic input of instruments built according to this principle solely derives from the mechanical characteristics of such a damped spring mass system, i.e. the elastic constant K of the spring and the damping constant C.

Since, however, the spring characteristic K is not precisely constant upon the whole range of possible spring deformations, and is temperature dependant, some of the most recent seismometers are equipped with an electromagnetic counterforce system fed by a feed back loop, limiting spring deformations within a small range where k is assimilated to a constant value.

This design, however, does not eliminates distortions caused by spring inertia and friction and, for a given instrument, it is not possible to change its parameters K and C, a fact which limits its use to a chosen range of accelerations and frequencies. Moreover

In order to eliminate these shortcomings, some new designs have been recently patented: they use either magnetic or electrostatic forces or the force resulting from a special property of a super-conducting loop, called the Meismer effect, in order to levitate a seismic mass.

The levitation is obtained through the action of one or several retroactive loops commanded by optical or capacitive sensors measuring the movements of the seismic mass in relation to the frame of the instrument.

The present invention belongs to this class of new designs but differs from existing products and known patents on several points which make its originality and its value.

Prior to discussing these points, we shall list and briefly describe existing relevant patents and give a detailed description of the present invention in its various implementations

Today's high quality seismometers and based on expensive multi-axis spring-damper elements with complex compensation systems. Electrostatic levitation of large spheres in high vacuum is the principle of some high precision gyroscopes.
A three axis active magnetic suspension seismometer, described in the U.S. Patent No 5,565,665 issued to Biglari et al., shows a limited sensitivity, caused by the sensing system, and a not symmetric behavior of the vertical axis. Magnetic suspension and rotation of small spheres was done by J. Beams, but with only one controlled axis.

Description of the present invention:

Implementation a :

Six electromagnets are diametrically disposed in pairs along three orthogonal axis
A small size ferromagnetic body is levitated and its position controlled along three axis

In the favored embodiment of this invention as a seismometer, (see Figure 4), the outside frame is an empty cylinder of homogeneous ferromagnetic material.
By convention, we shall call O its center of gravity and Oz its axis.
Also by convention we shall call Ox and Oy two axis located in the plane perpendicular to Oz and containing O, Oxyz being a direct trihedral.

In this favored embodiment as a seismometer the seismic mass is a spherical body of homogeneous ferromagnetic material.

When it is in its original position, the center of this spherical body is located in O.

Circular covers made of the same ferromagnetic material close both ends of the cylindrical outside frame.

Therefore the volume inside the frame of this seismometer (inner volume), is fully protected from any measurement bias caused by changes of outside magnetic conditions.

Seals between the cylinder frame and its covers close hermetically this inner volume which is equipped with a port in order to be put under vacuum whenever necessary for eliminating any bias due to atmospheric convection and friction.

Centered respectively on the Ox and Oy and located symmetrically with regard to point O, two sets of coils, each set made of two symmetrical coils facing each other create opposed magnetic fields.

Inside each coil, at its inner end, an axial sensor, centered on axis Ox or Oy and very rigorously positioned at pre-set distance from the Oz axis, provides instant and highly accurate measurements (+ or – 0.5µm) of its distance to the seismic mass along Ox or Oy as a function of time.

The two measurement values given by the set sensors centered, for example, on Ox, provide the basis for a differential measurement of the displacement of the seismic mass along the Ox axis and the same can be said for the set centered on Oy.

A third set of two coils with their corresponding axial sensors is centered on the Oz axis and both coils are located in rigorously symmetrical positions with regards to O.

It operates exactly like the two other sets described above.

The distance to the seismic mass of each sensor is sent in the form of a variable tension signal which, in order to remove any unwanted residual noise, is fed to an analogical filtering module.
The filtered signal in then converted to digital values in an ADC converter and the information is multiplexed and processed in a micro-controller.

The micro-controller:

1°) Calculates the displacement of the seismic mass as time functions measured along the axis Ox, Oy and Oz.

2°) Calculates the counterbalancing force necessary in order to bring the seismic mass back to its initial position, with its center in O, thus insuring its levitation.

3°) Sends the necessary instructions to a feedback loop commanding the current to the corresponding coils

4°) Calculate the value of the time function representing the acceleration of the seismic wave from the knowledge of the time functions representing the displacement of the seismic mass and the counterforce applied to it.

5°) Initial conditions being known, this information can be also used by the micro-controler to calculate both the speed of the seismic wave and the corresponding ground movements as a function of time.

Such a design could also be described as using 3 active magnetic bearings with Ox, Oy and Oz for axis and centered in O for keeping in levitation a rotor consisting of a spherical seismic mass made of homogeneous ferromagnetic and equally centered in O.

Here the advantage is that we can choose the value of the damping (d) and the spring constant (k) as we wish. The value of d and k is a parameter that we can choose in he controller. Moreover we can even define precisely triggers that characterize the limits between the borders of differents seismic events and this way the sensors can vary its damping and spring constant according to the nature of the seismic event.

This design can be made very compact thanks to the use of only one single sensor.

Thanks to differential measurements the precision of the measurements is high and not affected by temperature variation.
Moreover, the whole device is magnetically shielded and thus not affected by ambient magnetic waves.

If we apply the void inside the system, we can avoid the disturbance of the buoyancy forces and enhance the precision of the measurements.

Implementation b :

As for "implementation a" a magnetic levitation of a spherical mass is performed with three degrees of freedom control. Six vertically arranged electromagnets create opposing forces in three orthogonal directions. Magnetic permeable cores bring the magnetic field near to the sphere, reducing losses. The sensing system is composed of two red or infra-red laser diodes and two 4-segments photodiodes orthogonally placed in a horizontal plane between the upper electromagnets and the lower electromagnets. Therefore, positions x, y, z of the sphere can be measured. Afterwards, the x, y positions are rotated by 45 degrees and fed back to a PD controller as well as the z position.

The acceleration along the three orthogonal axis, defined by the electromagnets, is represented by the difference of the calculated control current of two opposing electromagnets.
Horizontal arrangement of the electromagnets 3b,4b,5b and 6b (same plane of the sensing system) could be a variant for this configuration.
In order to spin the spherical mass, a motor function can be added to the device by superposing a two-phase sinusoidal or square signal to the control current of the electromagnets 3b,4b,5b and 6b.

Advantages of the present invention :

The invention proposed has a symmetrical behaviour along three axis, therefore acceleration in three orthogonal directions can be detected.
Since the mass is magnetically levitated with active control, parameters like stiffness and damping can be varied over a large range in order to adjust the natural frequency. Both position signals and current signals can be used to determine acceleration. The addition of the motor function will transform the accelerometer in a gyroscope.

Applications :

This invention can be used as an accelerometer, a gravimeter, a tiltmeter or a seismometer. With the addition of the motor function one can use it as a gyroscope. Application fields are seismology, inertial navigation (mobile robots...), structural monitoring, geology (gravimeter) ...

Magnetic levitation and rotation of sub-millimetric spherical rotors

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Keywords

High-speed rotation, small spherical rotors

Abstract

To achieve high spinning speed, spherical rotors with less than 1 mm diameter have been levitated. A small device (50 [mm] x 50 [mm]), with a magnetic actuator that controls one degree of freedom of the rotor, an optical sensing system, and a two-phase induction motor has been designed and realized to perform levitation and rotation of small spherical rotors. In order to achieve a high spinning speed, spherical rotors with less than 1 mm diameter have been levitated.

1. Introduction

The experience presented is based on a paper of 1946 entitled "The Production of High Centrifugal Fields" [1]. In this paper, Jesse Beams of University of Virginia has magnetically levitated and spun small spherical rotors down to 0.794 [mm] diameter to their bursting speed. With the smallest rotor tested, they achieved in vacuum a spinning speed of 23'160'000 [rpm]. Afterwards, practically no further research was carried out in this field.

Our goal is, to reproduce these results with actual technologies, to minimize the device for the experience, and to levitate and spin even smaller rotors at very high speed.

The most critical problems are the generation of the very high speed rotating magnetic field to spin the rotor, as well as the detection of the spinning speed. Others challenges are the position sensing of rotor, and its stabilization.

In this paper we present a new, smaller configuration in order to levitate and spin sub-millimetric spherical rotors and first experimental results.

2. Experimental Setup

2.1 Overview

The device is composed of a magnetic actuator and an analog PD controller to stabilize the rotor position, an optical sensing system to measure the rotor position, and a two-phase induction motor. Lateral stabilization is passive. The rotors are steel spheres, as normally used in ball bearings. Two different rotors are considered with diameters of 1 [mm] and 0.5 [mm] respectively. The device for levitating and spinning the two rotors is identical.

2.2 Actuator

The actuator function is to compensate the mass of the rotor, and to stabilize its vertical position. In order to increase the magnetic field generated by the actuator, a ferrite core is placed inside the coil and a half spherical core end is used to facilitate horizontal stabilization of rotors with different diameters (figure 1a and 1b).

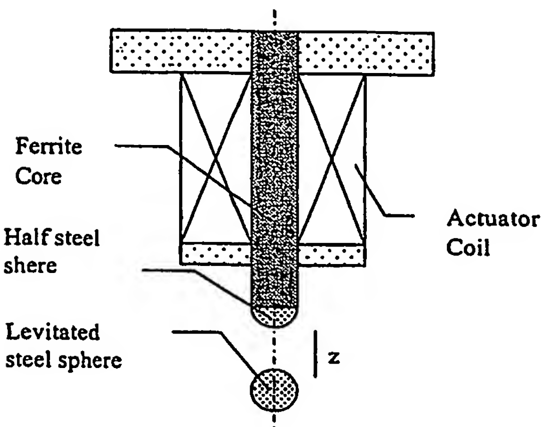


Figure 1a : Schematic view of the magnetic actuator

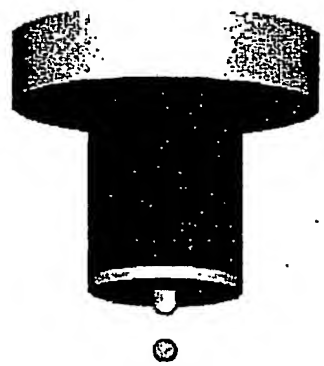


Figure 1b: 3D view of the magnetic actuator

The inductance of the coil is approximated by the following expression:

$$L(z) = L_0 + \frac{\Delta L}{1 + a \cdot z} \qquad (1)$$

where z is the distance between the rotor and the end of the actuator, L_0 is the inductance of the coil without the rotor, ΔL is the maximal variation of the coil inductance and a is a fitting parameter.

2.3 Position sensing system

The system to measure the rotor position is composed of a laser source, a lens, and a photodiode (figure 2).

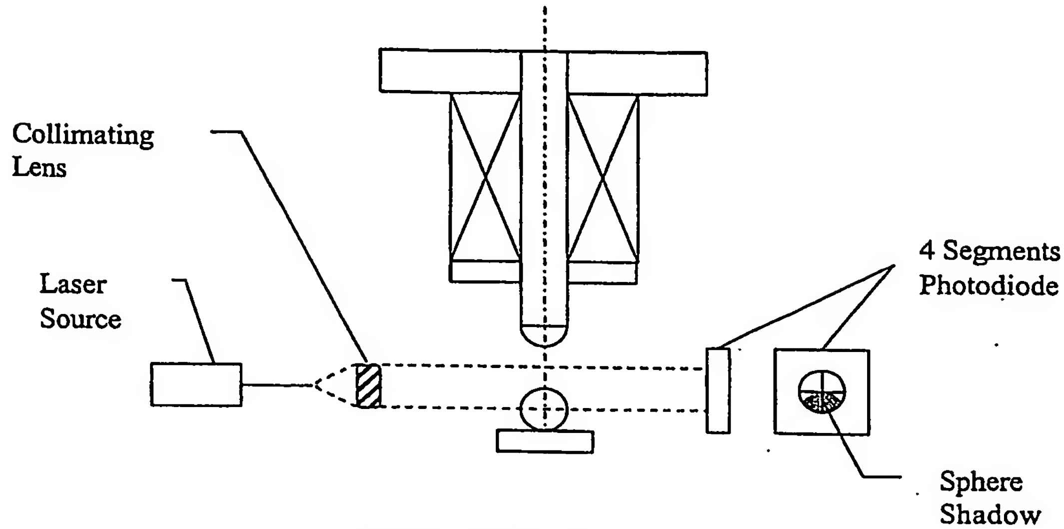
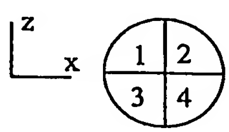


Figure 2: Position sensor principle

Red light, generated by the laser source, is guided to the device by an optical fiber. The laser is collimated with a small lens of 1 [mm] diameter, and illuminates the rotor. The four segments photodiode with a [1 mm] diameter sensing area placed behind the rotor, detects its shadow. Therefore the vertical movement and one horizontal movement, i.e. perpendicular to the laser beam, can be measured. The vertical displacement signal is used for the active control, and it is obtained with the following expression:



$$z = (1+2) - (3+4)$$

So, when the rotor is in the centre of the beam, the output signal of the sensing system is equal to zero.

2.4 Motor

At ultra-high spinning speeds, i.e. beyond 1 million rpm, stator eddy current losses become an important limiting factor in an electrical motor. High resistivity, or non-conductive materials must be considered for the coil cores and the stator, this way eddy current losses will be reduced. For a first try, a two-phase induction motor with a stator without conductive materials is designed with a minimum number of pole pairs, while the rotor must be conductive in order to operate as an induction motor.

Stator

The stator is composed of two coils per phase, that are serially connected (figure 4) and this results in a total inductance of 82 [μH] and a resistance of 3 [Ω]. As the number of the pole pairs is equal to one, the frequency of the stator rotating magnetic field corresponds to the frequency of the currents injected into the motor coils.

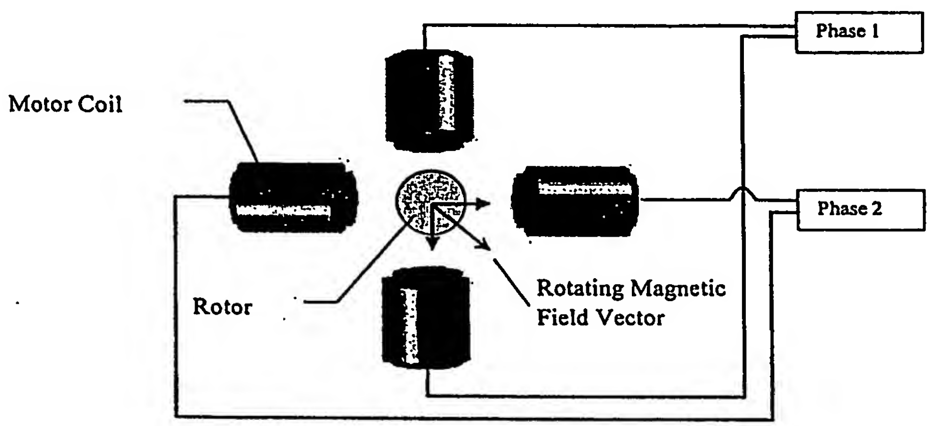


Figure 4: Rotating magnetic field

Figure 5 shows a drawing of the motor support with the four coils and the position sensing system. The coil cores are made out of heat resistant polymer (POM) and the support is made out of transparent polymer (PC). The air gap between two facing coils is 3 [mm], imposed by the crossing of the laser beam.

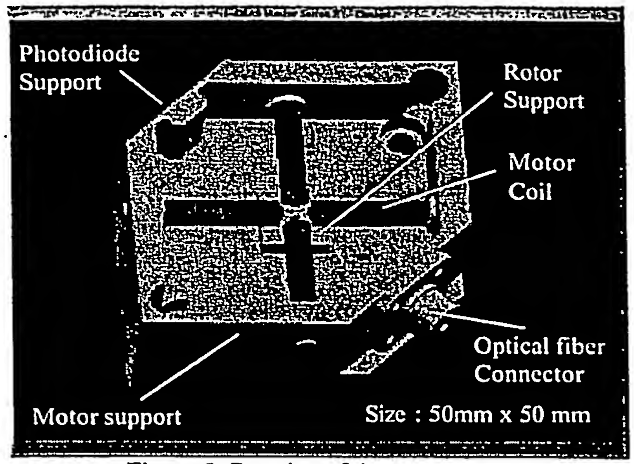


Figure 5: Drawing of the motor support

2.4.1 Rotor

As the rotor is a conductive material, eddy currents are generated in it by the stator rotating magnetic field. Following the principle of an induction motor, a torque is produced to spin the rotor.

2.5 Motor Driver

To create the high speed rotating magnetic field, a driver with an integrated H-bridge is chosen. Supply voltage is up to 50V, maximum output current is 2A and a maximum switching frequency of 250 kHz. With this driver, and a slip equal to zero, the rotor can theoretically achieve a maximum rotational speed of 15'000'000 rpm.

2.6 Speed measurement

The sub-system for the spin speed measure is not yet integrated into the device presented. The principle for the speed measurement is to partially change the reflectivity of the rotor, and to detect reflection variations during spinning of the rotor (figure 6).

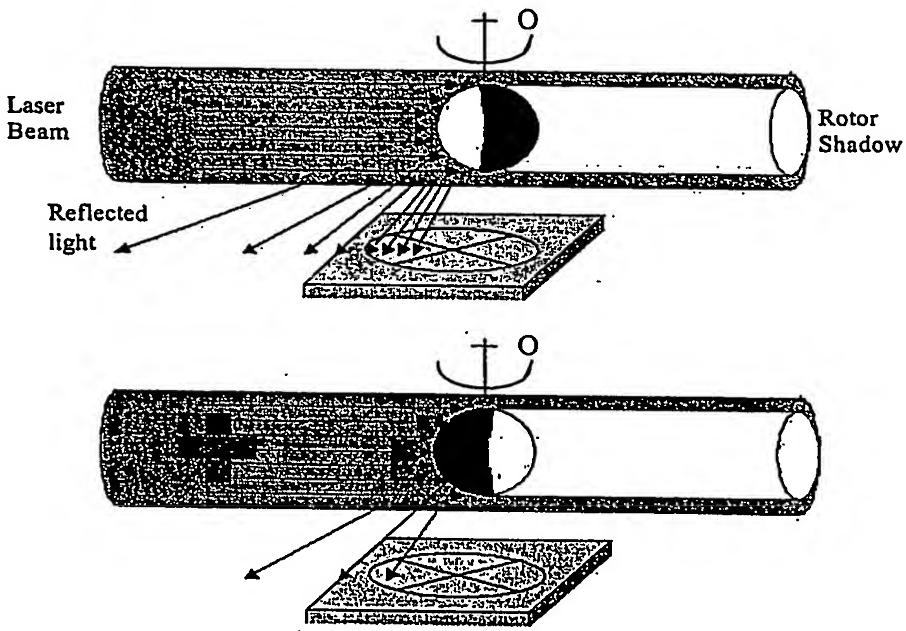


Figure 6: Principle for the speed measure

Reflected light from the rotor will illuminate the photodiode which is placed under the rotor. With one half of the rotor darkened, the frequency of the intensity variations, detected by the photodiode, will correspond to the spinning frequency. In order to have a maximum intensity variation, a well defined rotation axis has to be guaranteed.

3. Results

Levitation of the 1 mm rotor and the 0.5 mm rotor was successfully achieved (figures 7a, 7b and 7c). The starting position of the rotor was on a clean aluminum foil placed at the center of the PC support. At these small dimensions interaction forces between the support and the rotor are not negligible, therefore these elements were frequently cleaned to permit the rotor levitation.

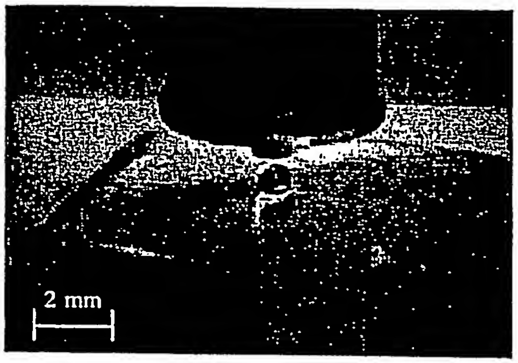


Figure 7a: Levitation of a 1mm rotor

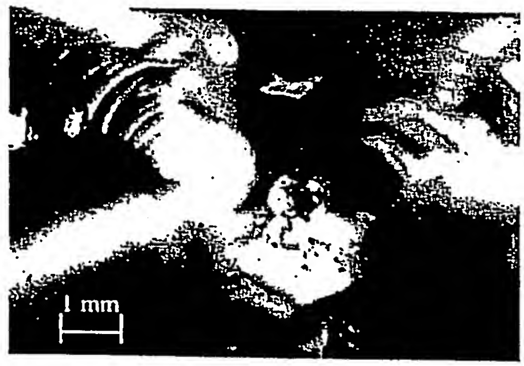


Figure 7b: Levitation and rotation of a 1 mm rotor

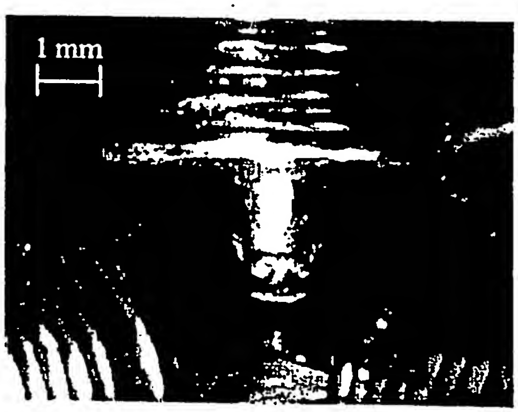


Figure 7c: Levitation and rotation of a 0.5 mm rotor

The motor function was also tested with satisfactory results. The 1 mm and 0.5 mm rotors were stably spinning up to the critical speed. Near this speed, a horizontal vibration occurs and the rotor is radially destabilized. The speed detection system is not yet realized. Table 1 resumes some device characteristics:

	1 mm Rotor	0.5 mm Rotor
Actuator bias current [mA]	543	112
Actuator air gap [mm]	1.5	0.75
Motor coil-Rotor air gap [mm]	1	1.25
Position sensor sensitivity [V/m]	3500	3500
Position sensor working range [mm]	0.6	0.4

Table 1: Device characteristics

4. Conclusions and Outlook

A small device to levitate and spin small rotors (0.5 [mm] and 1 [mm]) was realized with successful levitation and rotation. In order to increase spinning speed, and thus pass critical speeds, radial motion needs more damping (active or passive) [2].

Further improvements of the device will be the design of a new motor with smaller air gaps and ferrite cores, the introduction of an active radial stabilization, and the implementation of the speed measurement.

5. References

[1] J.W. Beams, "The Production of High Centrifugal Fields", Journal of Applied Physics, 1946, pp. 886-890

[2] A. Boletis, H. Bleuler, "Achieving Ultra-High Rotational Speeds", Proceedings of the 8th International Symposium on Magnetic Bearings, Mito, Japan, Aug. 26-28, 2002

Claim

1. Three axis active magnetic levitation for inertial sensing systems.

Abstract

The invention relates to high spinning speed spherical rotors which can be levitated.

Drawings

Implementation 2 :

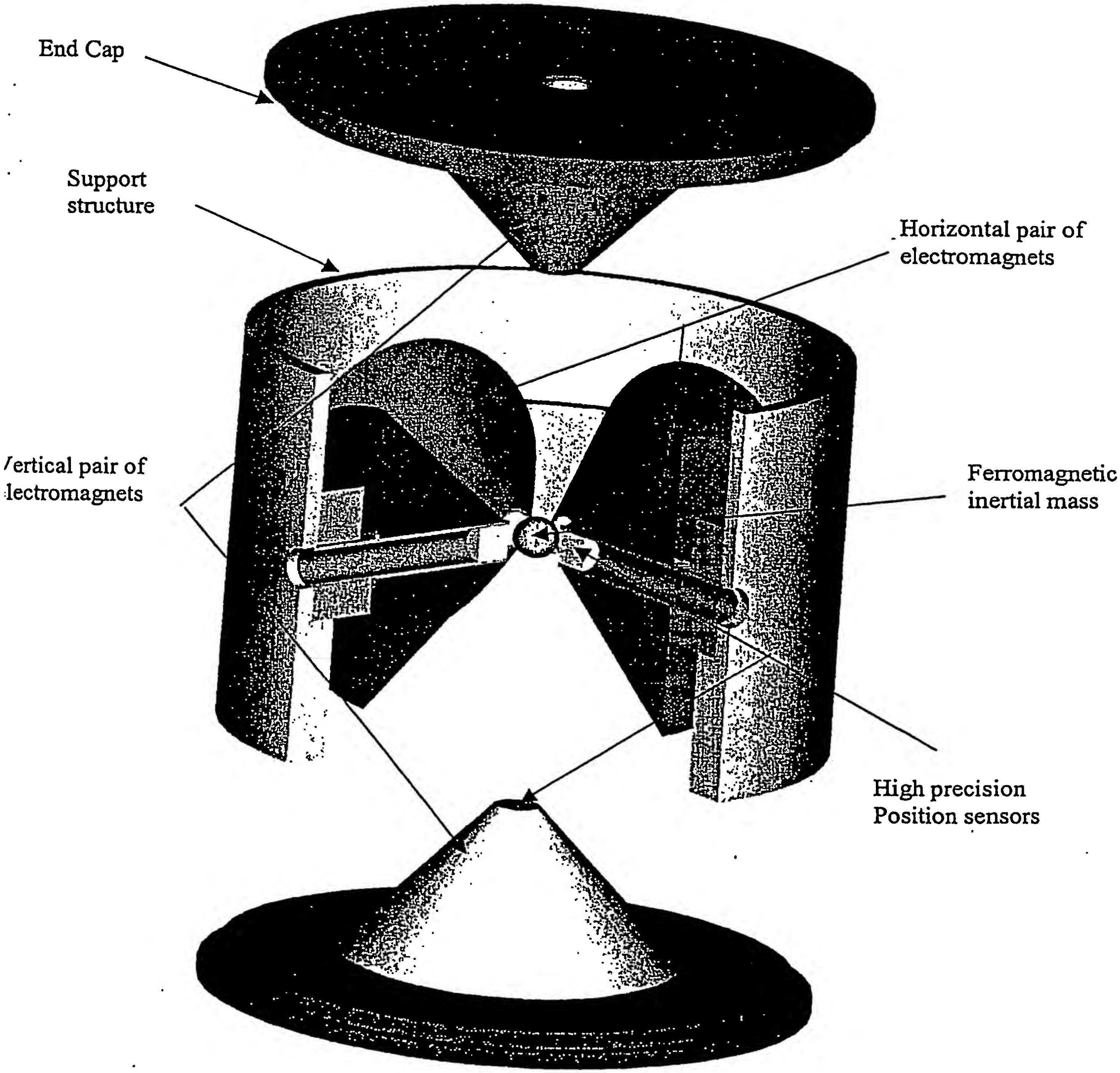


Figure 1

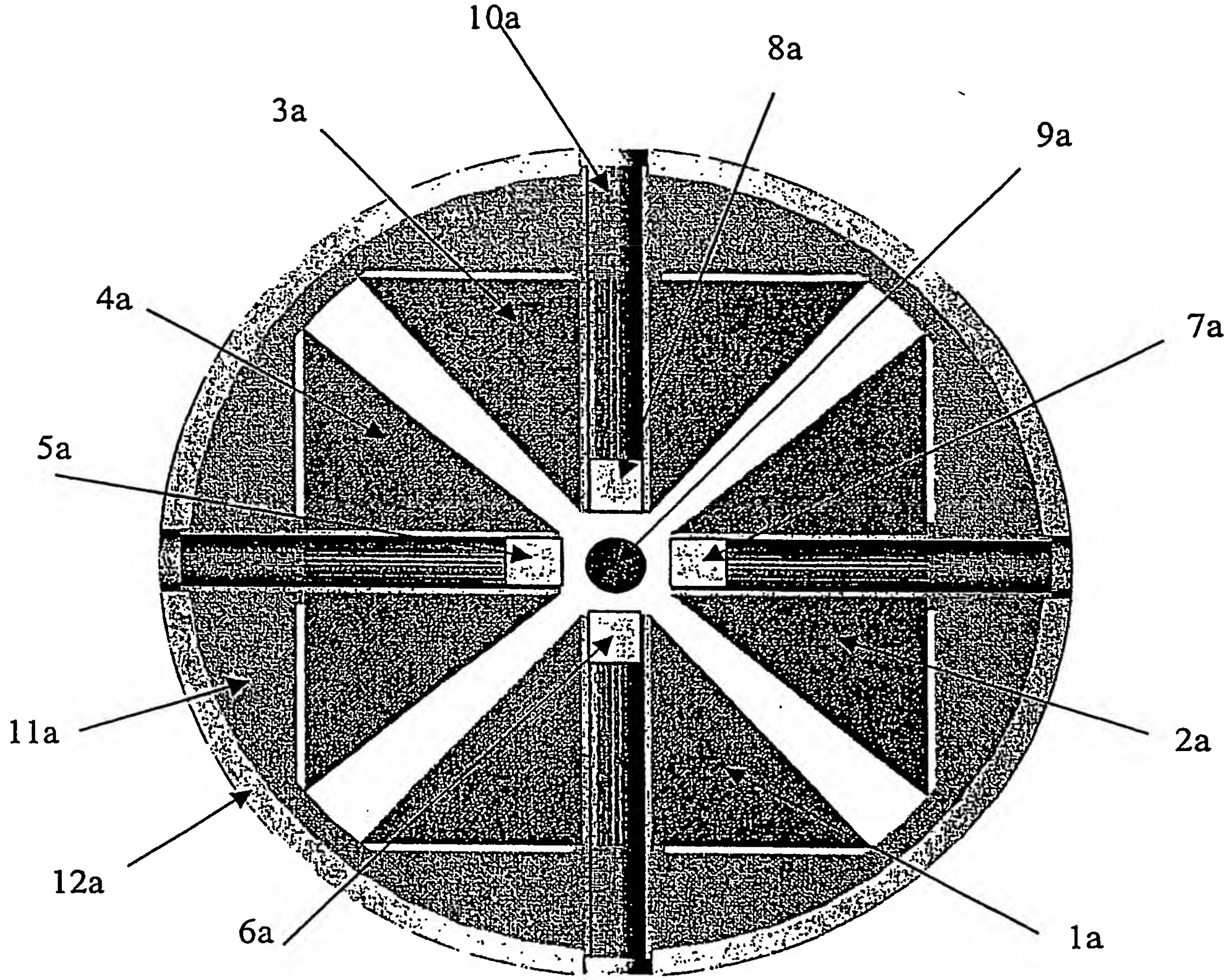


Figure 2 : Horizontal cut (O,X,Y)

Legend of configuration 2:

1a, 2a, 3a, 4a : Coils
5a, 6a, 7a, 8a : High precision position sensors
9a : ....Ferromagnetic sphere
10a : ....Coil armature
11a : ....Holding structure for the horizontal electromagnets
12a : ....Support structure

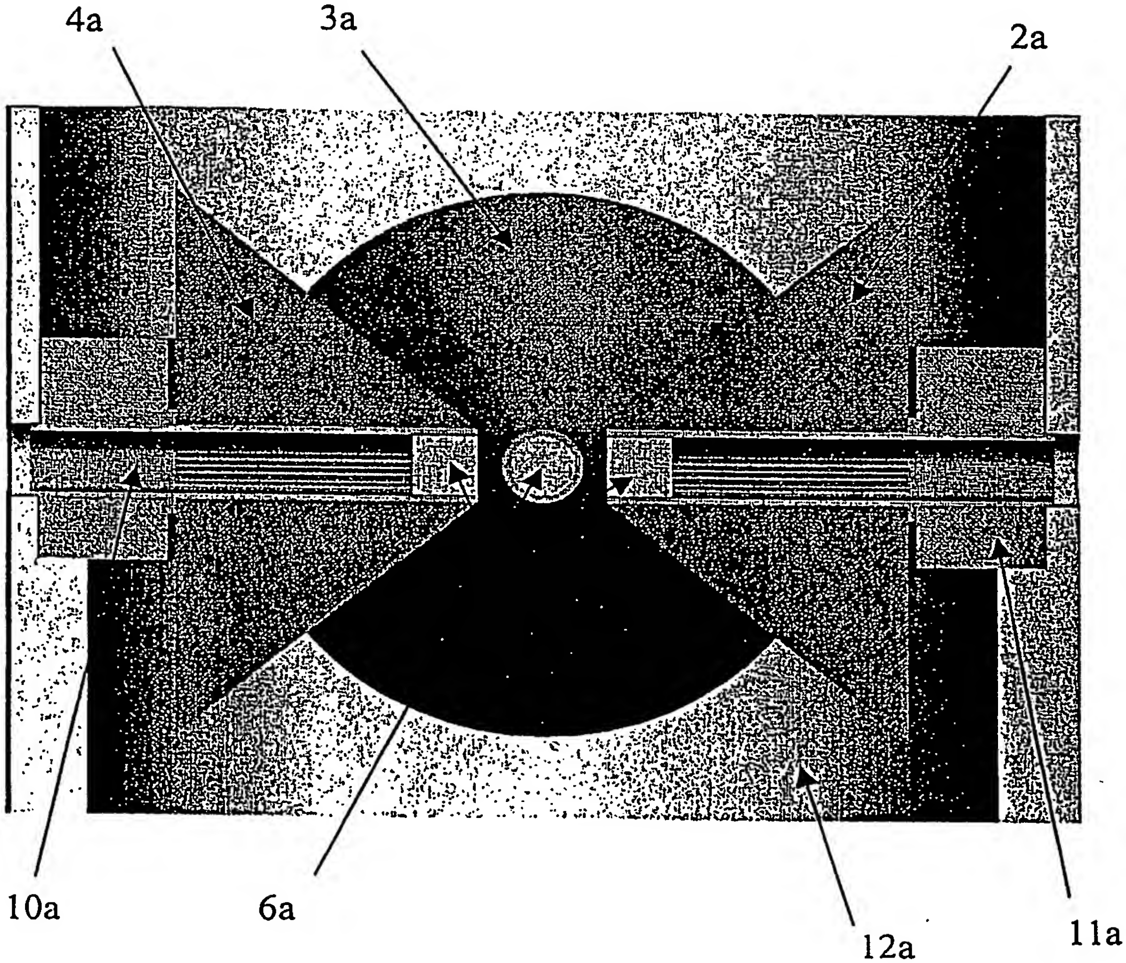


Figure 3 : Vertical Cut (O,Y,Z)

Implementation b :

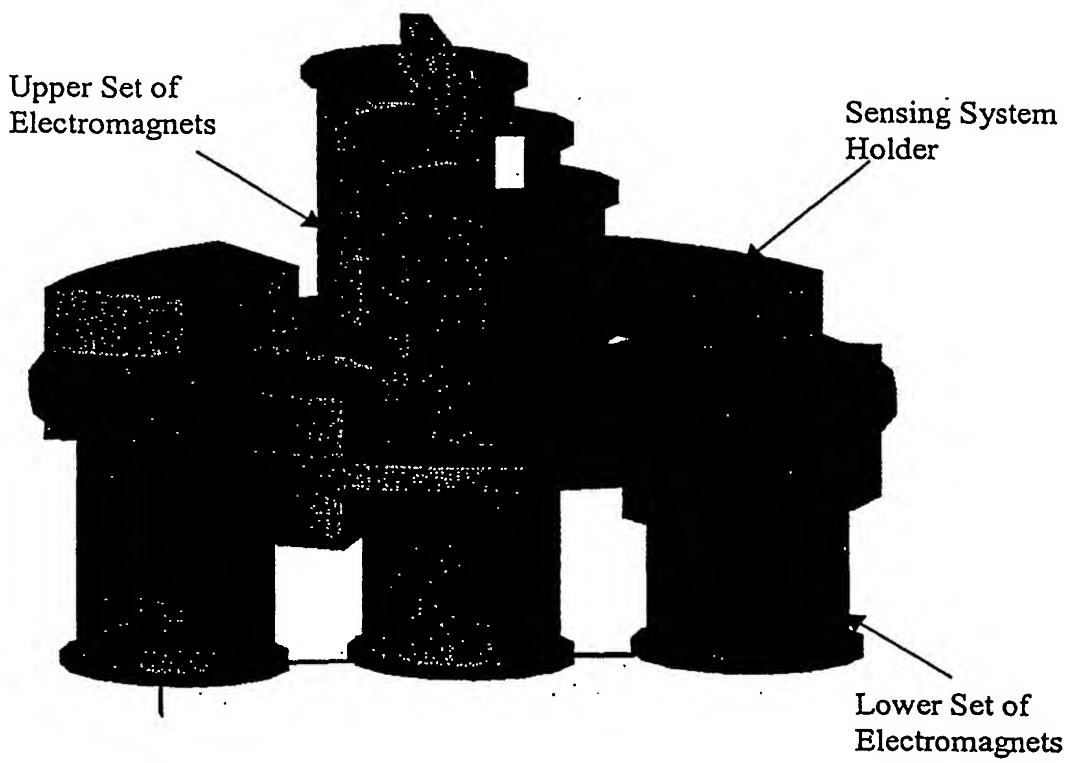


Figure 4

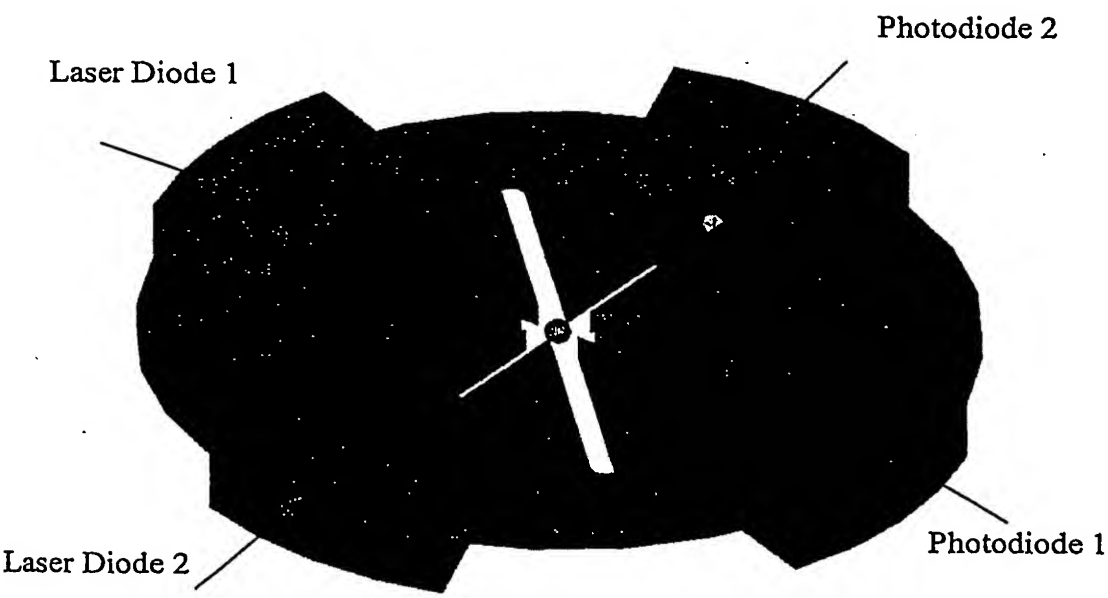


Figure 6